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PRIORITY DISPATCHING IN A
LABOR AND MACHINE LIMITED
PRODUCTION SYSTEM

by

Donald Albert Ludwig

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(Date)

Professor in Charge

Chairman of the Department of
Industrial Engineering

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ABSTRACT

This study considers the effect of priority dispatching in a labor and machine limited production system. A simulation model of an actual shop is developed using GASP II. The shop is characterized as a flow shop with cycling in which lots are subject to stochastic yields and reworks. Five labor sections, each operating on three shifts, exist in the shop.

Three queue disciplines (FCFS, FISFS, and SPT) are considered in combination with six labor assignment disciplines (LQ, LLT, LLT/NPM, FISFS, SPT, and SLT). All of these rules may be implemented without an information system. The various alternatives are evaluated with respect to mean flow time, standard deviation of flow time, lots in-process, inventory value, average position of lots in-process, labor and machine utilization, and frequency of labor reassignments. Simulated results are tabulated and a brief discussion of the various alternatives is included.

In general, the FISFS queue discipline was found to perform at least as well as FCFS on all measures of performance. The SPT queue discipline tended to minimize the mean flow time, lots in-process, and inventory value, but yielded a large standard deviation on flow time. The labor assignment rules which sought to reduce shop congestion (by minimizing the number of bottlenecks) yielded the best performance on the majority of the shop measures. Combination rules, involving scheduling of individual shop sections, were found to further improve the performance of the system.

CHAPTER I

INTRODUCTION

Background

Since the Industrial Revolution, organizations have grown in size and complexity. As this growth continues, the managerial decision-making process becomes increasingly complex, and the effective allocation of available resources over the entire organizational structure becomes an extremely difficult task. Operations management studies are but one response to the need for a systematic means of accomplishing this task. Objectives of operations management include maximum resource utilization, minimization of costs, and the maintenance of a high level of service through timely fulfillment of demand. These goals must be met within the constraints of available resources, be compatible with labor considerations, and be consistent with the overall objectives of the corporation. Furthermore, efforts to accomplish any one of these goals may work against accomplishment of the other objectives. For example, level of service may be improved by increasing inventory levels, but this in turn increases capital investment, thereby increasing incurred costs (in the form of inventory carrying charges, for example). Conversely, efforts to decrease costs by decreasing the size of the labor force may lead to a lower production capacity, and thus may affect level of service adversely, even though labor utilization may increase in the process. Due to the antithetical nature of these goals, management must consider the relative (rather than absolute) importance of each and optimize based on some composite measure of effectiveness (such as utility).

When an organization has limited resources, decisions must be made to allocate these resources in a way that will maximize the effectiveness of the organization. In the past 15 years, considerable research has been directed at organizations which can be classified as service centers or queuing systems. The majority of these studies assume a single resource constraint in the system, such as the number of servers in a tool crib or the number of machines in a job shop. In more recent years, researchers have turned to the study of systems with multiple resource constraints. It has been recognized that most actual operating systems are constrained by a number of scarce resources, and that a realistic study of these systems necessitates consideration of all constraints. In addition, the cost of limited resources continues to increase. This adds to the need for solutions to problems of effectively allocating these resources.

Statement of the Problem

The objective of this thesis is to study the effects of various resource scheduling procedures in a dual-resource constrained production system. The constraining resources are the shop labor force and shop machine capacity. The size of the total labor force will be held constant, as will be the number of machines in the shop. Six labor assignment disciplines and three queue disciplines will be investigated. The study will be carried out on a simulation of an actual shop manufacturing integrated circuits. The model is a revision of the one developed by D. D. Newhart[20,21] and J. W. O'Leary.

A review of the literature is presented in Chapter II. As stated by Newhart[21], the shop is characterized as a flow shop with cycling. Lots passing through the shop are subject to stochastic yields and reworks. Multiple channels exist at some facility centers. A further description of the shop is presented in Chapter III. Chapter IV discusses the priority disciplines to be investigated and the experimental design considerations. Chapter V presents the results of the experiments. Because the simulation is a model of an actual shop, all results have been scaled to preserve the proprietary nature of the data. While the absolute meaning of the results is thus destroyed, the relative relationships remain intact, thereby permitting comparison of the alternative rules.

CHAPTER II

LITERATURE REVIEW

Introduction

The literature review in this chapter will be primarily concerned with dual-resource constrained systems, and in particular with studies of labor and machine constrained systems. The reader is referred to work by Conway, et. al.[7] for detailed studies of simple machine limited systems. Most studies of machine limited systems have been carried out on small hypothetical systems. Studies on machine and labor limited systems by Nelson[15], Maggard[11], and others indicate that the results of experiments are highly dependent on the absolute size of the labor force and the shop, and the number of labors relative to the number of machines. Consequently, care must be taken when attempting to generalize the results of studies on labor and machine constrained systems.

Empirical and Simulation Studies

Previous to 1965, very little information was available in the literature concerning labor and machine limited systems. One of the earliest studies which prompted interest in multiple-resource constrained production systems was an empirical study by R. T. Nelson[14] in which an actual job shop was studied over a three-month period. Nelson concluded that while the arrival process was approximated by a Poisson distribution, the service time frequencies were found to be neither exponential, hyper-exponential, Erlang, hyper-Erlang, nor log-normal distributed. This led to the conclusion that a single resource constrained model was not an adequate representation of many real world production systems.

In 1964, R. D. Harris[8] conducted a similar study and found that the job-shop under study could not be modelled by the Erlang distribution. Harris concluded that an operator and machine together form a system that is more complex than that represented by a single-resource constrained Erlang model. Harris proposed that a dual-resource constrained queueing model (i.e., a machine and labor limited model) be considered as a more accurate representation of the shop.

One of the first reported simulation studies on a labor-limited production system was conducted by Morton Allen[1]. Allen considered a labor limited job shop characterized by a declining production demand. For this study, the work force was divided into classes based on the machines which could be operated by the laborers in the class. The flexibility of the work force was varied by varying the number of classes. Allen concluded that for industries experiencing fluctuating demand, a small, flexible, and highly skilled labor force was preferable to a larger, less flexible, and less skilled labor force.

In 1967, Nelson[16] presented results of a series of simulation studies of a labor and machine limited production system. The initial study was centered on the evaluation of alternative labor assignment procedures and queue disciplines in a hypothetical job-shop with four machines and a varying number of laborers (from one to four). Nelson studied three queue disciplines and five labor assignment procedures. The queue disciplines were first-come-first-served (FCFS), first-in-system-first-served (FISFS), and shortest-imminent-processing-time-first (SPT). The five labor assignment rules were RANDOM, FCFS, FISFS, SPT, and Longest Queue. A FISFS labor assignment rule, for example, would dispatch an available laborer to the machine at which the job with the earliest arrival to the shop was awaiting service. Nelson found that the rank order of the mean and variance of the time in the system for the three queue disciplines was consistent with that of previous studies on simple machine-limited systems. Of the three queueing disciplines studied, the SPT rule minimized the mean time in the system but had the highest variance on the time in the system. Of the five labor assignment rules studied, the Longest Queue rule resulted in the best performance on the mean and variance of time in the system. Nelson also observed that varying the queueing disciplines had a much larger effect on the flow statistics than varying the labor assignment procedures.

In the same study and later studies[16,17,19], Nelson also experimented with the size of the labor force, the degree of centralized control over labor assignment, and the individual labor efficiencies on different machines. By varying the labor efficiencies, varying degrees of work-force homogeneity could be simulated. From additional experiments in which the degree of centralized control over labor disposition was varied, Nelson found that as the degree of control increased, the mean and variance of the flow times decreased. Higher degrees of centralized control, however, did tend to reassign laborers more frequently under certain labor assignment rules. Additionally, Nelson's studies assumed an instantaneous reassignment of laborers, suggesting the possibility of further studies which include a time lag or penalty for labor transfers.

Other studies by Nelson[19], Maggard[11], and Hogg[10] have dealt with homogeneous versus non-homogeneous labor forces. The general results of these studies indicate that a homogeneous work force is preferable to a less flexible, non-homogeneous work force in a manufacturing environment. It must be realized, however, that a homogenous work force may not be realizable in the real world due to the human limitations on laborers.

Analytical Studies

Thus far, discussion has been limited to empirical and simulation studies. In recent years, limited analytical results have been obtained on dual-resource constrained queueing systems. R. T. Nelson[15] was able to analytically determine an optimal control mechanism for assigning available laborers to machine centers at any time t in the interval $0 \leq t \leq T$. The objective was to minimize the total in-process inventory cost over the time period $0 \leq t \leq T$. The work force was assumed to be homogeneous, and completely flexible, and the queue discipline was arbitrary. Through further simulation and analytical study[17], Nelson concluded that a labor and machine limited queueing model could not, in general, be reduced to an equivalent machine limited model. Tackacs[23] considered the problem of a single server attending two classes of customers, each arriving at a separate queue. The result of this study, and an earlier study by B. Avi-Itzhak, et. al.[2], was to determine the distribution of waiting times in the system at steady state.

Due to the complexity of the problem, simulation has perhaps been the most successful means of analyzing the dual-resource constrained production system. More recently, simulation studies have been employed to verify analytical results and to aid in developing and testing hypotheses related to the dual constrained system. The current investigation is a continuation of this earlier work, and will deal with resource scheduling in a particular dual-resource constrained shop.

CHAPTER III

MODEL DEVELOPMENT

Introduction

This chapter is devoted to a description of the pertinent characteristics of the actual production shop and the simulation model, and to a discussion of model validation. The model used in this investigation is a revision of that written by D. D. Newhart and J. W. O'Leary of the Western Electric Company[20].

Shop Characteristics

This section will be concerned with the characteristics of the actual shop which affect lot movement, processing, and waiting times. The actual integrated circuit shop is operated three shifts per day, and can best be described as a flow shop with cycling. Lots flow through the shop according to one of three predefined sequences of operations. Each lot passes through a sequence of 139 to 162 operations, depending on lot code. Lots are input to the shop at a constant rate during the first and second shifts; ten lots, each lot initially composed of 100 silicon wafers, are started each day. The product type of the wafers in each lot is the same for all wafers in the lot and is known at the time the lot is started.

Within the shop there are 66 facility or machine centers. Some facility centers have parallel processing channels capable of performing identical operations. The majority of the facility centers have one or two channels, but ten or more duplicate channels exist in certain instances. During processing, all lots return to a particular group of facilities nine or ten times depending on the lot routing (cycling). These "cycling" facilities are primarily photo-resist operations. A flow diagram of the integrated circuit shop for a typical code routing is shown in Figure 1. In the diagram, Section 2 is the photo-resist area. From the diagram, it may appear that Sections 1 and 3 are also cycling facilities. This is not the case, since lots returning to these sections will reenter at different points in the sections, and thus do not cycle through the entire operational sequence. The reentry point for a lot in these sections is determined by the progress of the lot through the shop.

As each lot is routed through the shop, the number of wafers in the lot is continually decreasing. This gradual decrease can be attributed to two main factors: wafer breakage or rejection of defective wafers at in-process inspection stations. Occasionally, an entire lot is rejected, usually as the result of operator error. Yield data (available from shop records) has been incorporated into the model.

Another factor affecting the progress of lots through the shop is lot rework. At in-process inspection points, wafers failing inspection are either scrapped or recycled for rework on the preceding three to six operations. If a decision is made to rework a

SHOP FLOW DIAGRAM

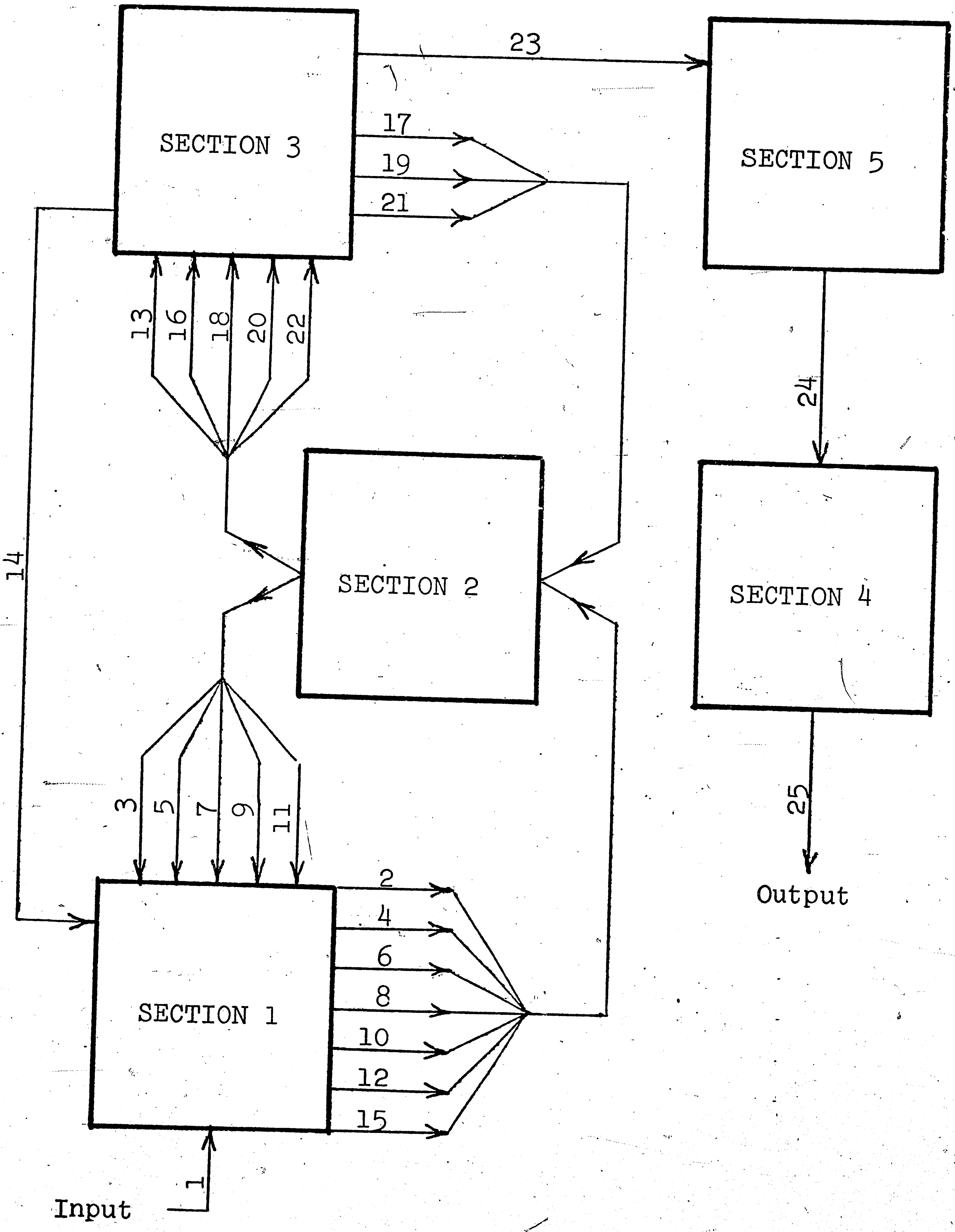

FIGURE 1

portion of a lot, the good portion of the lot is held in storage while the defective wafers are reworked. The two portions of the lot are reunited after rework is completed and proceed as a single lot for further processing. The occurrence of rework is a probabilistic event, as is the percentage of a lot requiring rework. Rework data was available from shop records, and has been incorporated into the model.

The processing time at a given facility is made up of either wafer-dependent time or a combination of wafer-dependent and wafer-independent times. An example of wafer-dependent time is inspection, or the loading and unloading of an oven. The time wafers spend in an oven is an example of wafer-independent time. Both a laborer and a facility are utilized during wafer-dependent time; only a facility is required during wafer-independent time. Since lots experience yields as they move through the shop, the processing times in the photo-resist area tend to be less each time a lot returns to these facilities. Also, because rework lots are usually smaller than the non-rework lots, a rework lot will tend to have faster processing times.

As illustrated in Figure 1, there are five sections in the shop under study. The number of shop laborers varies from section to section and from shift to shift within the sections. Laborers do not normally transfer between sections, nor between shifts.

Within each section, two classes of laborers exist: base and non-base. Non-base operators normally perform such jobs as layout operations, material handling, and process checking. Base operators perform those operations which directly affect the progress of lots through the shop. Both base and non-base operators are periodically employed in non-productive labor such as experimental work for an engineer, clean-up operations, and time away from the job due to company business or personal reasons. For this reason, the number of "effective" laborers (workers involved strictly in productive labor) in each section is often less than the on-roll workforce size. This feature has also been modelled in the simulation.

As stated previously, the shop operates on three shifts per day. At the beginning of each shift, each base laborer is assigned to a facility center. This labor assignment, or dispatching, is usually performed by the layout operator for each section. In the actual shop, a laborer is usually assigned to the facility center having the most work in queue. When assigned to a facility center, the laborer will generally remain at that center as long as work exists in queue. There is, however, a small probability of the laborer being reassigned while work still remains in the original queue. After all work is completed, the laborer is reassigned to a different center. The maximum number of laborers employed at a given facility at any given time is limited. In many cases, this maximum number is less than the number of processing channels in the center. This occurs as the result of space limitations or because certain multiple-channel facilities (e.g., ovens) may be operated by at most one laborer.

Model Construction

This section will present a brief description of the simulation developed to model the integrated circuit shop. As stated earlier, the model used for this investigation is a revision of that developed by D. D. Newhart and J. W. O'Leary. The original model was a machine-limited model programmed in GASP II. The revised model, which is also programmed in GASP II, is a machine and labor limited model. In the process of model revision, all non-GASP subroutines were changed and several event routines were added.

There are eight major types of event routines in the current model. These account for:

1. The arrival of a lot to the shop.
2. An end of service on a machine operation.
3. An end of service on a labor operation.
4. Clearing of finished lots from the model.
5. A shift change.
6. Calculation of in-process inventory.
7. Printing and reinitialization of statistics.
8. Printing of snap-shot statistics.

The arrival event inputs a lot to the system. The product code and lot size is determined at the time the lot is started. This event is rescheduled to occur at specific intervals of time during the first and second shifts of each day.

The second and third events are end-of-service events which occur each time a machine or laborer finishes processing a lot. As stated previously, the processing time at a facility for a given operation is comprised of either wafer-dependent time or a combination of wafer-dependent and wafer-independent times. Wafer-dependent time utilizes a facility and a laborer, while wafer-independent time, or machine time, utilizes only a facility. The simulation schedules the end-of-service on labor first, utilizing a laborer and a machine. When the end-of-service on labor occurs, an end of service on the machine is scheduled if further machine processing of a lot is required. The laborer is made available for processing of another job at the same facility center, or is dispatched to a different center if no work remains at his present station. An available worker is also dispatched to another center if no open channels exist at his present facility center. When a lot finishes processing at a facility, the appropriate yield calculations are made and the lot is checked for possible rework. The lot then proceeds to its next operation, and is queued or placed into service, as determined by worker and machine availability at that operation.

The fourth type of event collects statistics on finished lots and removes these lots from the system. All finished lots are stored in a designated file which is cleared every fifty simulated hours. Statistics on lots in the file are collected as this clearing operation takes place.

The next event type is the shift change which is scheduled to occur every eight hours. At each shift change, the number of laborers available for the next eight hours is determined for each shop section. The number of laborers available is a random percentage of the number of people on-roll; the distribution of this percentage is normally distributed with a given mean and standard deviation based on actual shop data. Those workers not available are either absent or will be utilized in work not directly related to the progress of integrated circuits through the shop. After the number of available laborers has been determined for each section, the workforce is dispatched to facility centers by section. As in the actual shop, once assigned to a facility center a laborer tends to remain at that center for the remainder of the shift, provided work remains in queue. Whenever a laborer finishes processing a lot, there is a 5% probability of his returning to a central section dispatcher for reassignment. If a laborer returns to central control, that laborer will be reassigned to any feasible facility center within his section, according to the labor assignment rule for the section (a feasible facility center is one in which work exists in queue and an open work station exists). A one minute setup penalty is incurred if the labor is assigned to a facility center different from his previous assignment. Once at a facility center, the laborer will process lots according to a predetermined queue discipline.

The sixth type of event is a periodic event which computes the value of the in-process inventory at specified intervals of time. The number of lots in-process, the number of wafers, and the total inventory value are computed. Inventory value is based on standard cost data of the product at specified points in the sequence of operations, and involves a "value-added" calculation.

The seventh type of event is scheduled to print and reinitialize statistics at predetermined points in time. This event was incorporated into the model to aid in collecting and reporting inventory and utilization statistics over different intervals of the simulation runs.

The last type of event is scheduled to print "snap-shot" statistics for the shop. The statistics reported are the length of queues at each facility center, the number of facilities busy at each center, and the number of laborers busy in each of the five sections. This event occurs every one-hundred hours, and provides a means of monitoring the shop through-out a simulation run.

The points listed below summarize the characteristics of the integrated circuit shop and the features incorporated into the simulation model.

1. The shop can be characterized as a flow shop with cycling.
2. Some facility centers have more than one machine capable of performing the same operation (multiple channels).
3. Lot size tends to decrease as a lot progresses through the shop.
4. Some lots may experience a zero yield.
5. Lots may be split, temporarily, due to rework requirements.
6. Processing times may be both independent of and dependent on lot size.
7. The shop operates on three shifts and the number of laborers varies by shift and by section.
8. There are five sections in the shop, each assumed to have its own homogeneous work force.
9. A time loss is incurred when a laborer is shifted between facility centers (setup).
10. Machines must be started by a laborer but may operate without a laborer being present (see point 6).
11. The number of laborers busy at a facility center at a given time may be constrained to be less than the number of facility channels.

The following assumptions, common to many other studies, are also included:

1. No machine may process more than one lot at a time.
2. Transit times of lots between facilities is negligible.
3. Lap-phasing is not permitted, i.e., a portion of a lot may not proceed to its next operation until the entire lot has finished processing on the current operation.
4. Both a laborer and a facility must be available for a lot to begin processing.
5. Machine breakdown and maintenance are not considered.
6. No preemption is allowed.
7. The probability of a laborer returning to central control is the same for all laborers within a given section.

Model Validation

The shop statistics of primary concern in validating the simulation model included the average flow time of a lot through the shop, the average number of lots in the shop, the average in-process inventory value, and the average size of a finished lot. To validate the model, the simulation was run for a period of 4000 hours to attain steady state. The model was then restarted from this preload point and run for an additional 10,000 simulated hours. The data collected for this 10,000 hour run was statistically tested using time series analysis and found to be trendless, thus confirming that steady state had been achieved. The model statistics were then compared to shop data and found to be in satisfactory agreement. In addition, the labor utilizations within the model maintained the same relative ranking, by section, as the labor utilizations in the actual shop. Other statistics, such as queue lengths, average machine utilizations, and average waiting times were also examined and found to be reasonable approximations to actual values. The model was thus assumed to be a valid representation of the integrated circuit shop. The shop status at the end of the 14,000 hour run-in was preserved as a preload for all further experiments.

CHAPTER IV

EXPERIMENTAL INVESTIGATION

Introduction

This chapter is divided into four major sections. The first two sections discuss the machine and labor scheduling rules examined in the current investigation; the third section discusses the measures of performance used in evaluating the alternative rules; the final section deals with experimental design considerations.

Queue Disciplines

Three machine queuing disciplines were examined in the experiments conducted. These included first-come-first-served (FCFS), first-in-system-first-served (FISFS), and shortest-imminent-processing-time (SPT). These particular disciplines were selected on the basis of their frequent occurrence in the literature and the relative ease with which any of these rules may be implemented in the actual shop. This latter feature is particularly important to the eventual application of experimental results within the actual operating system.

Since the three queue disciplines studied are well known, and are basically self explanatory, detailed discussion of their properties is omitted. The interested reader is directed to the work of Conway, et. al.[7] for a basic description of these rules.

Labor Assignment Disciplines

This section will describe the six labor assignment disciplines that were investigated. In terms of the actual shop, these rules correspond to those utilized by a labor dispatcher in assigning an available laborer to a shop workstation.

The first labor assignment rule is the longest queue (LQ) discipline. Under this rule, an available laborer is assigned to the feasible facility center with the largest number of lots in queue. (Once again, a feasible facility center is one at which work exists in queue and there exists an open channel for processing, subject to specified constraints on the total workers permitted at the center.) Ties are broken by sending an available laborer to the center with the least number of machines busy. Intuitively, the "best" place to assign an available laborer is to a "bottleneck" facility; the longest queue discipline is one means of scheduling on "bottleneck" facilities.

The second labor assignment rule is the largest-labor-time (LLT) discipline. This rule is simply an alternate means of identifying "bottleneck" facilities, similar to the LQ discipline. Under this discipline, an available laborer is dispatched to the facility center having the greatest labor content in queue. The rule is based on total expected labor time to complete processing on all lots currently in the queue of each feasible facility center. One would expect the LLT rule to be a better identifier of bottleneck facilities than the LQ discipline. However, more computational effort is required in implementing the LLT rule, and incremental performance gains must clearly be weighed against the cost of these additional computations.

The third labor discipline is a variation of the LLT rule. This rule is based on the ratio of the labor content in queue and the maximum number of laborers permitted to simultaneously process lots at the associated facility center. An available laborer is dispatched to the facility center which maximizes this ratio; the acronym for this rule is LLT/NPM. The rationale for this rule may best be explained by example. Assume that at time t facility centers i and j each contain work in their respective queues that is expected to require 10 hours of labor time. Further assume that no more than one laborer is permitted to work at center i at any given time and that no more than two laborers are permitted at center j. The minimum expected elapsed time to complete the work at center i is 10 hours, while at center j it is 5 hours. Facility center i clearly has a greater potential of becoming a bottleneck center. Under the LLT/NPM rule, the respective ratios are 10 and 5 and a laborer would be assigned to facility center i in an attempt to reduce this potential. Thus the LQ, LLT, and LLT/NPM rules seek to reduce shop congestion by minimizing the number of shop bottlenecks.

The fourth labor assignment rule studied was the first-in-system-first-served (FISFS) discipline. Within this discipline, the first lot in each feasible facility queue is examined to determine its starting time into the shop. An available laborer is assigned to the facility center at which the lot with the earliest arrival time is first in queue.[1] That is, a FISFS labor assignment discipline gives lots that have been in the shop the longest the highest priority. Such lots have usually completed a large part of their required processing, and thus maintain a high value in comparison with other lots (due to the value-added character of the process). A FISFS discipline, therefore, attempts to give the "most valuable" lots highest priority.

The fifth labor assignment rule is the shortest-imminent-processing-time (SPT) discipline. Under this rule, a laborer is dispatched to the facility center at which the lot with the shortest expected labor processing time is first in queue. Once again, this rule, as the previous rule, is based solely on attributes of the first lot in each of the feasible facility queues. It is well known that an SPT queue discipline yields superior performance on the mean job flow time but has poor performance on the variance of flow time. One may conjecture that an SPT labor discipline may produce results similar to the SPT queue discipline.

The sixth labor assignment discipline is the shortest-labor-time (SLT) rule. Under this rule, an available laborer is assigned to the facility center having the minimum labor content in queue. One might expect this rule to exhibit characteristics similar to the

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[1] It must be noted that a labor assignment rule does not preempt the queue disciplines. Once a laborer is assigned to a facility center, lots are serviced in the sequence determined by the center's queue discipline.

SPT labor discipline.

Throughout the simulation investigation both queue and labor disciplines were implemented by shop section; that is, if an SPT queue discipline is to be implemented in a section, all facilities within that section process lots according to an SPT queue discipline. Similarly, all laborers within a section are dispatched according to a single labor assignment rule. During the first 18 experiments performed, the labor and queue disciplines were held fixed across all five shop sections in the model. Additional experimentation was concerned with various combination rules involving scheduling of individual sections of the shop.

Measures of Performance

All measures of performance discussed in this section and presented in the following chapter are based on simulation results which may correspond to actual shop information. To preserve the proprietary nature of this data, all results presented have been scaled. While the absolute meaning of the results is thus destroyed, the relative relationships remain intact, thereby permitting comparison of the alternative rules.

Objectives of operations management include maximum resource utilization, minimization of costs, and the maintenance of a high level of service through timely fulfillment of demand. The measures of performance discussed in this section have been formulated from these objectives.

The first measure of performance considered is the mean flow time of lots through the shop. It is clearly advantageous to deliver the product to the customer in the minimum time. Furthermore, a small flow time allows the shop to be highly responsive to changes in demand. Additionally, a decrease in through-put time implies a reduction in the number of lots in-process (from the flow equation), and is therefore economically desirable. The mean flow time and average number of lots in the system were reported for each alternative tested.

In addition to mean flow time, shop management is concerned with the variance of flow time, an indication of the variation in the manufacturing interval. A small flow-time variance indicates that excessively long or excessively short job processing times are unlikely; the variance of job flow time is thus a measure of the predictability of meeting due dates. The standard deviation of flow times was reported for each alternative. In addition, histograms of the flow times are presented in Appendix A.

The next measure of performance is the average in-process inventory value. At least two types of costs can be associated with in-process inventory: storage costs (a function of the number of lots in the shop) and capital and insurance costs (a function of the inventory value). Traditionally, one would expect a decrease in the number of lots in the shop to be accompanied by a corresponding decrease in the total value of the in-process inventory. This is not necessarily the case. Under various decision rules, a shop may operate with a relatively low number of lots in-process. However, the value of these lots may be relatively high. The value of each lot is dependent on the lot size and the amount of labor and material already invested in that lot (value added). For the shop under investigation, lot sizes are not uniform throughout the shop due to in-process yields. These factors indicate that the number of lots in-process is not an adequate measure of in-process inventory value. Consequently, the total average in-process inventory value (based on actual value-added data) is calculated and reported for each of the alternatives. Also, to illustrate the relative position of the lots in-process, the average lot position is reported. Average position is defined as:

$$\text{Average Position} = \frac{\sum_{I} (\text{Wafers}) \times (\text{Operation Number})}{\sum_{I} (\text{Wafers})}$$

where I = the set of all lots in-process.

A high average position indicates that a large number of wafers have completed the majority of their required processing, and thus implies that the average value per lot is high.

The traditional measures of resource utilization (labor and machine utilization factors) were also reported. Overall labor and machine utilization have been reported and analyzed for the various scheduling alternatives. In addition, labor and machine utilization factors by shop section are tabulated in Appendices B and C.

A final statistic of interest is the average number of setups per hour. A setup is incurred each time a laborer is transferred from one facility center to a different center, and corresponds to a "start-up" operation in the actual shop. This statistic is thus a measure of non-productive time caused by the movement of laborers between facility centers. In the actual shop, a laborer undergoes a short acclimation period when starting a new job (learning). In an attempt to model this learning effect in the simulation, a time penalty is charged in each setup instance, and is added to the basic processing time for the operation. The average total setups per hour for the entire shop are discussed in Chapter V, while the average setups per hour by section are tabulated in Appendix D.

Experimental Design Considerations

An initial consideration in the design of all simulation investigations is the starting configuration of the model. Conway[5] suggests three possible starting conditions:

1. Start the system "empty and idle" for each alternative tested.
2. Use a common set of starting conditions for each alternative.
3. Test each alternative with its own "reasonable" starting condition.

The second and third strategies are generally more efficient than the first. Conway suggests that the second strategy is preferable to the third because one should compare different alternatives under as nearly identical conditions as possible. In addition, excessive computer time may be required to create the many preload configurations necessary for the third strategy. A single preload, representative of the current shop operating configuration, has been employed as a starting point for all alternatives. More precisely, the simulation was run for a total of 14,000 simulated hours to obtain a validation of the basic model. (This run was made using a first-come-first-served queue discipline at all facility centers and a longest queue labor discipline in each of the five labor sections). The ending configuration of this "validation" run was preserved and used as a preload for the remainder of the experiments.

The next decision involved the choice of an appropriate sample size. To collect flow time statistics, a sample size of 400 lots was chosen and ten such samples were collected for each alternative. The model was designed so that lots starting in the system during the time interval $t_0 < t \leq t_1$ constitute the first sample, lots starting in the period $t_1 < t \leq t_2$ constitute the second sample, and so on. The time intervals were chosen to provide the same number of finished lots in each sample. The input job stream was identical for each alternative tested. The simulation was run (and input to the system continued at a constant rate) until all the sample cells were completed or until 30,000 hours of simulated operation was reached. The 30,000 hour ending time was at least 5,000 hours longer than the average time required to complete the last cell under a FCFS queue discipline and LQ labor discipline. The sample size of 400 is the same order of magnitude as the number of lots in-process and was chosen so that no more than 50% of the lots in adjacent cells would be in the shop at any given time.

The next decision in experimental design involved the recording and computation of in-process inventory. Because the determination of the in-process inventory value requires significant computational effort, it was decided to record the inventory at discrete time intervals rather than as a continuous statistic. Consequently, inventory was determined at time intervals which are approximately 10% of the average flow time of lots through the shop. Ten observations of the inventory constituted one sample and ten such samples were taken for each run. Each time the inventory was computed, the number of lots in-process, the number of wafers, the average position, and the total inventory value were determined.

In addition to maintaining the same input job stream for each alternative, an additional variance reduction technique was employed. Because the processing time of a lot is a function of the lot size, and lot size is a random variable determined by stochastic yields, it is possible to process a different number of wafers under each of the different alternatives, leading to a bias in experimental results.

Consequently, to insure that each lot would experience the same yield history, regardless of the alternative tested, a separate random number stream was employed in calculating in-process yields. The seed for this stream was formed by multiplying the lot position by the lot starting time (a unique number for each lot in the shop). After computing lot yield, the simulation returns to the original random number stream. This technique was developed by Newhart,[21] and ensures that the same number of wafers are processed in each experimental run of the model.

CHAPTER V

ANALYSIS OF RESULTS

Introduction

A total of 25 experiments were performed to investigate the effect of priority dispatching on shop performance. The first 18 experiments tested the six labor assignment disciplines in combination with the three queue disciplines. For each of these 18 experiments the same (labor, queue)-combination was employed in each of the five labor sections of the shop. Based on the results of these initial experiments, additional experiments were made using combination rules. The last seven experiments investigated mixed rules in an attempt to improve the overall shop performance by capturing the "best" characteristics of the various disciplines. The prime objective in employing these rules was to minimize the average flow time while maintaining acceptable performance on the other shop measures, primarily the standard deviation of flow time. The first section of this chapter presents the results of the first 18 experiments. The last section discusses the rationale for choosing the various mixed rules and presents the results achieved through their use.

Performance of the Universal Rules

The means of the observations for the various measures of performance are presented in Tables 1 through 8 for the first 18 experiments. As previously stated, these results have been adjusted by a constant factor to preserve the proprietary nature of the data. Note that the

Table 1

MEAN FLOW TIME

Labor Discipline	Queue Discipline		
	FCFS	FISFS	SPT
LQ	1078.4	1078.8	867.1
LLT	1059.8	1037.1	870.6
LLT/NPM	1073.2	1003.0	856.3
FISFS	1130.7*	1154.7*	1095.3*
SPT	1516.5*	1406.7*	738.6
SLT	1807.9*	1375.2*	776.8*

*These alternatives did not achieve steady state during the simulation run. The values recorded for these alternatives are the means of the last 400 lots.

Table 2

STANDARD DEVIATION OF FLOW TIMES

Labor Discipline	Queue Discipline FCFS	FISFS	SPT
LQ	59.64	20.26	907.29
LLT	69.53	21.31	949.32
LLT/NPM	67.71	19.84	863.99
FISFS	29.67	24.24	113.99
SPT	167.03	25.43	1340.93
SLT	58.43	27.81	277.46

Table 3

AVERAGE LOTS IN-PROCESS

Labor Discipline	Queue Discipline		
	FCFS	FISFS	SPT
LQ	444.8	443.2	406.5
LLT	435.6	426.7	395.3
LLT/NPM	440.7	414.5	385.8
FISFS	460.4*	467.9*	444.0*
SPT	629.7*	557.8*	427.8
SLT	747.9*	552.4*	660.5*

*These alternatives did not achieve steady state during the simulation run. The values recorded for these alternatives are the means of the last 10 observations of inventory.

Table 4

IN-PROCESS INVENTORY VALUE

Labor Discipline	Queue Discipline FCFS	FISFS	SPT
LQ	1103.1	1092.3	1083.5
LLT	1076.8	1045.1	1035.2
LLT/NPM	1086.1	1016.1	1003.8
FISFS	1081.9*	1098.5*	1049.5*
SPT	1550.9*	1411.2*	1158.6
SLT	1843.7*	1303.8*	1721.7*

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* These alternatives did not achieve steady state during the simulation run. The values recorded for these alternatives are the means of the last 10 observations of inventory.

Table 5

AVERAGE INVENTORY POSITION

Labor Discipline	Queue Discipline		
	FCFS	FISFS	SPT
LQ	90.82	84.01	82.88
LLT	88.38	77.44	75.90
LLT/NPM	87.57	76.45	74.10
FISFS	28.83	27.55	29.54
SPT	110.81	110.96	93.24
SLT	87.06	26.33	51.73

Table 6

LABOR UTILIZATION (%)

Labor Discipline	Queue Discipline		
	FCFS	FISFS	SPT
LQ	82.673	82.442	82.569
LLT	82.389	82.156	82.372
LLT/NPM	82.227	82.833	82.896
FISFS	81.294	81.161	81.821
SPT	80.635	80.991	81.700
SLT	76.713	79.515	77.354

Table 7

MACHINE UTILIZATION (%)

Labor Discipline	Queue Discipline FCFS	FISFS	SPT
LQ	35.641	35.403	35.555
LLT	35.508	35.255	35.383
LLT/NPM	35.303	35.529	35.610
FISFS	34.655	34.605	33.990
SPT	34.537	34.841	35.124
SLT	33.010	33.945	33.372

Table 8

SETUPS PER HOUR

Labor Discipline	Queue Discipline FCFS	FISFS	SPT
LQ	36.01	34.71	35.97
LLT	36.78	36.08	36.35
LLT/NPM	34.78	34.12	34.65
FISFS	47.71	48.82	48.90
SPT	50.34	48.75	50.50
SLT	50.21	48.55	49.47

flow time, number of lots in-process, and inventory value did not reach steady-state during the simulation run for several of the alternatives tested. Consequently, ending values were reported for these experiments. In all other experiments, a steady state condition existed for the entire run, and the results reported are the means of the ten consecutive samples taken.

The first performance measure of interest is the average flow time of lots through the shop. One objective of operations management is the minimization of manufacturing cycle time. This allows the shop to be more responsive to demand fluctuations and results in a smaller number of lots in-process. The general trend of the flow times, average lots in-process, and total inventory value as effected by the labor and queue disciplines is given as follows:

Labor

(min.) LLT/NPM
LLT
LQ
FISFS
SPT
(max.) SLT

Queue

(min.) SPT
FISFS
(max.) FCFS

As in simple machine limited studies, the SPT queue discipline produced the minimum flow time of the three queue disciplines tested under each of the six labor disciplines. Though the average flow time is minimized, the SPT rule typically results in a high variance on lot through-put times. In general, under an SPT queue discipline, 1-2% of the 4000 lots for each experiment did not complete processing by the end of the simulation run. An (SPT, SPT) labor-queue combination resulted in 5% of the lots being unfinished. As a result, the mean and standard deviation of the flow times are understated for the SPT queue disciplines. This fact can be verified by comparing the ratio of the lots in process to the mean flow time; this ratio should be approximately 2.4 (the arrival rate) for each of the alternatives. Since the processing times are in part a function of the lot size, large lots are penalized under the SPT queue discipline. As a result, the lots that remain in inventory tend to be larger under SPT than those remaining under a FCFS or FISFS queue discipline. This fact is verified by comparing the number of lots in process under an SPT rule to the number of lots in-process under a FCFS or FISFS rule, and the respective inventory values under the different rules: the change in the inventory value is not as great as the change in the number of lots. In general, the FISFS queue discipline performed at least as well as the FCFS discipline with respect to mean flow time, number of lots in process, and inventory value. The one exception to this general pattern was observed under the FISFS labor assignment discipline. Excessive labor blocking is conjectured to be a possible cause for this result. (As defined by Nelson[17], "blocking" of labor occurs when there is work in queue at one or more service centers and one or more laborers are idle but cannot work at the centers because every machine is already occupied by a laborer). Under the (FISFS, FISFS) alternative, excessive queue build-ups were observed in the early operations in several of the labor sections. Of the six labor assignment disciplines investigated, the LLT/NPM, LLT, and LQ rules resulted in the minimum mean flow time, lots in-process, and inventory value. The rationale behind these rules was to identify bottleneck facilities and allocate laborers to these facilities. Of these three rules, LLT/NPM and LLT performed better than the LQ discipline. This effect was anticipated since LLT/NPM and LLT are better measures of the total work content at each of the facility centers and, therefore, would be expected to be better identifiers of bottleneck facilities. These rules, however, require additional computational effort and their advantages may be offset by this fact. It is interesting to note that the LLT/NPM labor rule shows an improvement over the LLT rule under an SPT or FISFS queue discipline but not under a FCFS discipline. The author has no logical explanation for this result. The SLT rule yields the worst performance of the six rules studied. Under this rule a laborer is assigned to the facility center having the smallest labor content in queue. As a result, bottlenecks are allowed to form and are given the lowest priority.

Average position of the in-process inventory is another statistic of interest. Average position is an indication of the relative amount of processing performed on the lots currently in-process. The average position for each of the 18 alternatives is given in Table 5.

The average position under the FISFS labor discipline is in general significantly lower than the average position for the other alternatives tested. A low average position indicates that a high percentage of the lots are held in early operations of the process. This reaffirms previous results in which large queue build-ups were observed in the early operations under the FISFS labor discipline. Observing the average position under the LQ, LLT, and LLT/NPM labor disciplines, it is apparent that the SPT queue discipline produces an average position lower than that achieved under a FCFS or FISFS queue discipline. As lots move through the shop they tend to become smaller due to in-process yields. Under the SPT queue discipline, these smaller lots are given priority and move through the shop sections more rapidly than larger lots. The lots that remain in inventory are thus larger lots which tend to be queued at the early stages of the process. The FISFS queue discipline also produces an average position that is less than the average position under a FCFS rule. Under the FISFS queue discipline the lots that have been in the system the longest are given highest priority and move through the shop more rapidly than new lots. The lots that remain in the system have later starting times and therefore have a relatively low average position.

The next measure of performance considered is the standard deviation of flow time. A smaller standard deviation of flow time implies a more predictable lot finishing date. A large standard deviation of flow time implies a possibility that lots will finish extremely early or excessively late. Lots finishing too early must be held in a finished product inventory until the required due date; lots finishing after their due dates may produce customer dissatisfaction. The standard deviation of flow times are presented in Table 2 for the 18 basic experiments performed. Histograms of the flow times are presented in Appendix A. As is evident in Table 2, the FISFS queue discipline yields the minimum standard deviation of flow time for each of the labor disciplines tested; the SPT queue discipline yields the maximum standard deviation. One may note that these results are similar to results observed in simple machine limited studies. No general pattern of flow time standard deviation was observed for the various labor disciplines. However, it is interesting to note that the FISFS labor discipline produces a relatively low standard deviation of flow times while the SPT labor rule results in relatively high standard deviations, a result similar to the queue discipline counterparts of these rules. The (SPT, SPT) alternative produced the maximum standard deviation of flow time.

The relative ranking of the labor assignment disciplines with respect to labor utilization is given below:

	Labor	Utilizations[1]
(max.)	LLT/NPM	82.7
	LQ	82.6
	LLT	82.3
	FISFS	81.4
	SPT	81.1
(min.)	SLT	77.9

This ranking tends to agree with the flow time ranking, a result that may be anticipated. Labor utilization is a function of the work to be performed and the number of laborers available. The total work to be performed is determined by the jobs input to the shop. Therefore, under steady state conditions, labor utilization has an upper limit set by the job input rate. As previously stated, the values of flow time, lots in-process, and inventory exhibited a positive trend for certain alternatives tested. No trend was observed, however, in the labor utilizations. This is an indication that some of the alternatives tested may never achieve steady state under the present shop configuration. The relative ranking of the machine utilizations under the various labor disciplines is approximately the same as that of the labor utilizations. This result is not surprising in a dual-resource constrained production system; the more severely constrained resource controls the utilization of the other resource.

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[1] These utilizations are the averages of those produced by the three queue disciplines.

The number of setups per hour was an additional measure of performance studied. Since there are fewer laborers in the shop than machines, it is necessary to move laborers between facilities to maintain lot movement. The number of setups per hour measures the amount of labor movement within the sections of the shop. A setup occurs each time a laborer moves from one facility center to another. Productive labor time is lost each time a laborer moves; it is thus beneficial to minimize the amount of labor movement without creating excessive bottlenecks in the shop. As is evident from Table 8, the number of setups per hour is affected significantly by the labor assignment discipline. The LQ, LLT, and LLT/NPM labor rules result in the least number of setups per hour while the SPT, SLT, and FISFS labor disciplines significantly increase the number of setups per hour.

This section has discussed the results of the first 18 experiments. Each of these alternatives was implemented universally across the shop. From the standpoint of overall shop performance, the best alternative tested thus far was the FISFS queue discipline in combination with a LQ, LLT, or LLT/NPM labor assignment rule. The FISFS queue discipline performed at least as well as the FCFS queue discipline on average flow time, lots in-process, and in-process inventory value. In addition, this rule yielded a minimum standard deviation of flow time. The LQ, LLT, and LLT/NPM rules maximized labor utilization while minimizing the number of setups per hour. The selection of a single labor discipline from these three must depend on a consideration of the computational effort required to implement the rules. The SPT queue discipline minimized the average flow time and lots in-process and consequently tended to minimize the in-process inventory value. A major failing of the SPT rule, however, is its extremely large standard deviation of flow time. The FISFS labor discipline is advantageous in that it gives priority to the oldest lots in the shop; yet it also produces excessive queue buildups at early shop operations. The SPT labor rule in combination with the SPT queue discipline produced a low value of flow time and lots in-process, but the standard deviation of flow time under this alternative was prohibitively large.

Performance of Mixed Rules

This section discusses the rationale behind the seven mixed rules investigated and the effect of these rules on shop performance. The primary objective in testing these rules was to minimize the mean flow time of lots through the shop while maintaining an acceptable standard deviation of flow time.

As stated in Chapter III, the shop is composed of five distinct labor sections. The laborers in each of these sections are under separate internal management organizations, making it possible to treat each section individually with respect to the implementation of dispatching rules. Because of differences in the relative position of shop sections, and the diverse characteristics of the sections, one would expect each section to react differently to the various labor and queue disciplines. To aid in the development of the various mixed rules, the labor and machine utilizations, and the number of setups per hour by section for the initial 18 experiments were investigated. The labor and machine utilizations are tabulated in Appendices B and C respectively, and the setups per hour by section are listed in Appendix D.

It is clear from Appendices B and C that there exists a significant difference between the average machine utilization and the average labor utilization. From these statistics, it appears that labor is the more limiting resource. In comparison with the labor utilizations in sections 2, 4, and 5, labor utilization in Section 1 is high (95%) while labor utilization in Section 3 is low (61%). Consequently, it is of primary importance to effectively allocate the "over-utilized" workforce within Section 1; similarly, the workforce in Section 3 appears "under-utilized," and a "less-than-optimal" allocation of labor is tolerable. The first mixed rule is a result of this reasoning. A LQ discipline was implemented in Sections 1, 2, 4, and 5, since these sections have the higher labor utilizations. A FISFS labor rule was employed in Section 3 in an attempt to improve the overall flow of lots through the shop. To further speed the flow of lots in Section 3, an SPT queue discipline was used. A study by Newhart[21] concluded that an SPT queue discipline in the photo-resist area (Section 2) and a FISFS queue discipline in the remaining areas resulted in a decreased average flow time without adversely affecting the standard deviation of flow time. On this basis, the SPT queue discipline was also implemented in Section 2, while Sections 1, 4, and 5 utilized a FISFS queue discipline. The first mixed rule thus has the following combination of labor and queue disciplines:

Section	Labor	Queue
1	LQ	FISFS
2	LQ	SPT
3	FISFS	SPT
4	LQ	FISFS
5	LQ	FISFS

The results of this rule are given in Table 9. The rule yields performance which approximates that of the (LLT, FISFS) labor-queue combination (discussed in the previous section) without requiring the additional computational effort necessary for an implementation of the LLT labor discipline. The average flow time was decreased by approximately 5% over the (LQ, FISFS) alternative and the standard deviation of flow time has increased slightly. However, the standard deviation is still far less than that observed under a FCFS queue discipline. The labor utilization increased slightly over that achieved by any of the previous alternatives, while the number of setups per hour remained at approximately the level achieved by a universal LQ labor discipline.

From these results, one may ask the question: Can further improvement in the flow time be achieved (without significantly affecting the standard deviation of flow time) by using an SPT queue discipline in

TABLE 9

MIXED RULE RESULTS

Rule Number	Flow Time		In-Process Inventory			Labor Utilization	Machine Utilization	Setups per Hour
	Mean	Standard Deviation	Lots	Value	Average Position			
1	1028.7	27.51	424.3	1049.5	84.57	83.060	35.640	35.26
2	882.6	1113.54	393.5	1041.6	83.27	82.874	35.668	36.15
3	1048.6	39.88	431.3	1069.8	84.14	82.669	35.475	35.16
4	1091.5	28.04	448.1	1103.3	83.74	82.374	35.381	34.76
5	948.1	24.50	393.0	966.7	77.07	83.110	35.687	33.56
6	1023.7	25.12	421.5	1031.9	76.15	82.411	35.355	34.17
7	997.0	25.63	411.3	1009.8	75.87	82.638	35.462	33.07

Section 1, the section with the highest labor utilization? In the second mixed rule, the SPT queue discipline was employed in Section 1 and the FISFS queue discipline was employed in Section 2, the cycling section. All other labor and queue disciplines remained the same as in the first mixed rule. The results of this experiment are shown in Table 9. The average flow time and lots in-process decreased significantly as a result of this rule but the standard deviation of flow time increased substantially. This leads to the conclusion that the standard deviation of flow time under the SPT queue discipline is a function of the utilization of available resources; with higher utilization, a larger standard deviation of flow time is observed. Note that it is the high labor utilization that causes this high standard deviation of flow time for the SPT queue discipline, a result that indicates the interdependence of labor and machine resources.

The third mixed rule studied the effects of implementing an SPT queue discipline in Sections 2, 3, 4, and 5 (the sections with lower labor utilizations) and a FISFS queue discipline in Section 1. The labor rules were the same as those employed in the two preceding rules. As shown in Table 9, the performance on flow time, lots in-process, and inventory value for the third rule is poorer than that achieved by the first mixed rule. In addition, the standard deviation of flow time is higher than that of the first mixed rule, yet lower than that of the second rule. Since lot size tends to decrease as lots move through the process, a FISFS queue discipline in the later sections of the shop is largely similar to an SPT queue discipline. However, under a FISFS rule, priority is based on lot starting time, thus maintaining a uniform movement of lots through these sections.

Having obtained a "good" combination of queue disciplines, one may turn to the determination of a combination of labor assignment disciplines which may further improve the shop performance. The fourth mixed rule replaced the FISFS labor discipline in Section 3 by the LQ discipline. The fourth rule is thus composed of the following disciplines:

Section	Labor	Queue
1	LQ	FISFS
2	LQ	SPT
3	LQ	SPT
4	LQ	FISFS
5	LQ	FISFS

The results achieved by this combination rule are given in Table 9. The flow time, lots in-process, and inventory value under this alternative are approximately the same as the results of the (LQ, FISFS) alternative discussed in the previous section. It was noted in the previous section that a FISFS labor discipline decreases the standard deviation of flow time, a result that is again observed by comparing the results of the first mixed rule to those of the fourth rule.

Since Section 1 has the highest labor utilization and since the majority of the inventory is apparently resident in this section, it would seem logical to implement the "best" labor-queue rule combination in this section. From the second mixed rule, it was observed that a FISFS queue discipline must be used in Section 1 to maintain an acceptable standard deviation of flow time. Since the LLT/NPM labor rule was found to perform quite well in combination with a FISFS queue discipline a (LLT/NPM, FISFS) combination was employed in Section 1, with all other labor and queue disciplines identical to those for the first mixed rule. The results of this fifth rule are given in Table 9. From Table 9, it is clear that a dramatic improvement is achieved in overall shop performance. The average flow time and lots in-process compare favorably with the (LLT/NPM, SPT) alternative discussed in the previous section. The in-process inventory value is the minimum of all alternatives investigated and the standard deviation of flow time is approximately equal to that experienced under a simple FISFS queue discipline. In addition, the total number of setups per hour does not exceed the number observed for any other alternative.

The dramatic improvement in shop performance achieved by this introduction of the LLT/NPM rule in Section 1 led to experimentation with this rule in other sections of the shop. The sixth rule tested had the following configuration:

Section	Labor	Queue
1	LLT/NPM	FISFS
2	LLT/NPM	SPT
3	FISFS	SPT
4	LLT/NPM	FISFS
5	LLT/NPM	FISFS

The results presented in Table 9 indicate that this rule does not perform as well as the preceding rule, a surprising result. The flow time, lots in-process, and inventory value are higher than those achieved by the fifth rule, but are lower than those achieved by most other alternatives tested. One logical explanation for this result seems to lie in the relationship between an SPT queue discipline and the LLT/NPM labor assignment rule. The LLT/NPM discipline assigns laborers to facility centers having the largest labor content per number of permitted laborers. Under the SPT queue discipline, the average size of lots in queue, and therefore the average labor content in each queue, tends to be higher than that for the same number of lots under a FISFS queue discipline. Thus the LLT/NPM rule tends to give priority to the facility centers containing these larger lots. A LQ discipline merely counts the number of lots in each facility queue and assigns a laborer to the center having the most lots awaiting service. A similar effect would be expected in Sections 4 and 5 under a FISFS queue discipline since the lots farthest along in the process tend to be the smallest. To test this conjecture, a seventh rule was designed.

In this rule, the LLT/NPM rule in Section 2 was replaced by a LQ labor discipline and all other disciplines remained the same as in the sixth mixed rule. The results are given in Table 9. An improvement over the sixth rule is observed in flow time, lots in-process, and inventory value. However, this last rule does not perform as well as the fifth rule, and the previous conjecture is thus neither confirmed nor disproved. A summary of the mixed rules studied is given in Table 10.

This chapter has presented the results of 25 experiments which studied the effect of priority dispatching in a labor and machine limited production system. The results of these experiments illustrate the dependence of shop performance on <u>both</u> labor and queue disciplines. In addition, it is clear that the effects of the various queue disciplines are not independent of the labor assignment discipline.

TABLE 10

CONFIGURATIONS OF MIXED RULES

Section	Rule 1	Rule 2	Rule 3	Rule 4
1	LQ , FISFS	LQ , SPT	LQ , FISFS	LQ, FISFS
2	LQ , SPT	LQ , FISFS	LQ , SPT	LQ, SPT
3	FISFS, SPT	FISFS, SPT	FISFS, SPT	LQ, SPT
4	LQ , FISFS	LQ , FISFS	LQ , SPT	LQ, FISFS
5	LQ , FISFS	LQ , FISFS	LQ , SPT	LQ, FISFS

Section	Rule 5	Rule 6	Rule 7
1	LLT/NPM, FISFS	LLT/NPM, FISFS	LLT/NPM, FISFS
2	LQ , SPT	LLT/NPM, SPT	LLT/NPM, SPT
3	FISFS , SPT	FISFS , SPT	FISFS , SPT
4	LQ , FISFS	LLT/NPM, FISFS	LQ , FISFS
5	LQ , FISFS	LLT/NPM, FISFS	LQ , FISFS

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

This thesis has studied the effect of various labor assignment and queue disciplines in a production system. The rules investigated may be implemented without the use of an information system. From the standpoint of overall shop performance, the best alternative of the universal rules tested was the FISFS queue discipline in combination with a LQ, LLT, or LLT/NPM labor assignment rule. It was found, in general, that the labor assignment rules which dispatch available laborers to centers containing the most work in queue perform the best on all measures of shop performance. The FISFS labor rule, while attempting to maintain a steady flow of lots through the shop, produced excessive queuing in the early operations of the shop. Consequently, a large in-process inventory, and relatively large job flow times were observed. The FISFS queue discipline performed at least as well as the FCFS rule with respect to average flow time, lots in-process, and inventory value. Performance trade-offs must be considered in comparing the results achieved by a FISFS queue discipline with those produced by an SPT rule. As has been shown in previous studies on machine limited systems, the SPT queue discipline tended to minimize the flow time and lots in-process, but produced a correspondingly large standard deviation of flow time. It was also found that the standard deviation of flow time under the SPT rule is a function of the resource utilization; the use of an SPT rule in a shop section with high labor utilization resulted in an extremely large standard deviation of flow time. Additionally, this investigation has shown that the improvement in inventory value produced by the SPT discipline was not as great as the improvement in the number of lots in-process, an important economic result.

Various combination rules were investigated in an attempt to capture the "best" characteristics of individual universal rules. The rule that produced the best results with respect to all measures of performance was the fifth mixed rule. The rule is given by the following combination:

Section	Labor	Queue
1	LLT/NPM	FISFS
2	LQ	SPT
3	FISFS	SPT
4	LQ	FISFS
5	LQ	FISFS

In an attempt to further improve shop performance, the LQ disciplines of this rule were replaced with the LLT/NPM labor assignment discipline. Interestingly enough, shop performance declined. Based on this result, it is conjectured that a LLT or LLT/NPM labor rule has a tempering effect on the SPT queue discipline. The validity of this conjecture was not verified in the current investigation, and remains an obvious area for further study. Indeed, the entire question of the inter-relationships of labor and queue disciplines should be explored further.

Throughout this investigation, a time loss of one minute was incurred each time a laborer was reassigned to a different facility center. This mechanism attempted to model learning effects experienced by operators who transfer between workstations frequently. As operators are transferred less, their efficiency at certain stations should begin to increase. Further consideration should thus be given to operator specialization and the possible inclusion of a heterogeneous, rather than homogeneous, labor force in the shop. In the present model, the workforce is assumed to be homogeneous within the shop sections.

Another parameter not considered in the investigation is the degree of central control over labor assignment within each of the five labor sections. For this investigation, the probability of a laborer returning to central control after completing a job was constant at 5% for each of the sections. A natural area for further investigation is a test of the effect of increasing this "control." Additionally, a consideration of the means by which an actual shop would implement stricter control is useful from an applications standpoint.

As stated previously, this investigation considered six labor assignment rules and three queue disciplines which can be implemented without the use of an on-line information system. Many more alternatives can be developed. For example, a labor assignment rule which considers the machine processing times (in addition to labor times) may improve shop performance. "Look-ahead" rules can be devised. Composite rules within labor sections should result in further improvement in overall shop performance. In addition, different queue disciplines on high and low demand items may improve shop performance without adversely affecting the level of service. The number of alternatives that can be tested through the aid of a simulation model of the type used in this study is basically unlimited.

This investigation has illustrated the importance of including labor as an active constraint in a production system, and indicates that multiple-resource constraints more accurately characterize the shop under study. Continued research in this area, through both simulation and analytical studies, should prove extremely fruitful in solving the problem of effectively allocating limited resources in the complex organizations that exist in the present industrial environment.

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APPENDIX A

FLOW TIME HISTOGRAMS

(FCFS Queue Discipline)

Cell (Hours)	Labor Discipline		
	LQ	LLT	LLT/NPM
0-700	--	--	--
700-800	--	.001	.001
800-900	.007	.038	.029
900-1000	.096	.101	.119
1000-1100	.530	.617	.474
1100-1200	.353	.220	.337
1200-1300	.014	.023	.039
1300-1400	--	--	.001

Note: Results of FISFS, SPT, and SLT labor rules are not presented here since those alternatives were not at steady state.

APPENDIX A (Cont'd.)

FLOW TIME HISTOGRAMS

(FISFS Queue Discipline)

Cell (Hours)	Labor Discipline		
	LQ	LLT	LLT/NPM
0-900	--	--	--
900-1000	.003	.242	.451
1000-1100	.731	.623	.549
1100-1200	.266	.135	--

Note: Results of FISFS, SPT, and SLT labor rules are not presented here since those alternatives were not at steady state.

APPENDIX A (cont'd.)

FLOW TIME HISTOGRAMS

(SPT Queue Discipline)

Cell (Hours)	Labor Discipline			
	LQ	LLT	LLT/NPM	SPT
0-300	--	--	--	.214
300-400	.021	.023	.009	.382
400-500	.137	.141	.095	.176
500-600	.256	.227	.229	.055
600-700	.201	.200	.231	.029
700-800	.111	.144	.154	.021
800-900	.075	.075	.083	.012
900-1000	.052	.042	.059	.009
1000-1100	.028	.027	.029	.007
1100-1200	.019	.016	.019	.005
1200-1300	.015	.016	.013	.004
1300-1400	.010	.010	.008	.006
1400-1500	.007	.007	.007	.002
1500-1600	.009	.007	.006	.002
1600-1700	.004	.008	.006	.003
1700-1800	.004	.004	.003	.002
1800-1900	.003	.003	.005	.002
1900-2000	.002	.004	.003	.001
2000-2100	.001	.003	.003	.003
2100-2200	.002	.003	.002	.002
2200-2300	.002	.002	.003	.001
2300+	.041	.038	.033	.062

Note: Results of FISFS and SLT labor rules are not presented here since those alternatives were not at steady rate.

APPENDIX B

LABOR UTILIZATIONS (%)

Alternative	Shop Section				
	1	2	3	4	5
LQ, FCFS	95.653	79.204	61.630	90.871	87.498
LQ, FISFS	95.720	78.985	61.284	90.523	87.245
LQ, SPT	95.962	79.338	61.392	90.509	87.191
LLT, FCFS	95.974	79.315	61.288	90.152	86.769
LLT, FISFS	95.352	78.644	60.822	90.549	86.885
LLT, SPT	95.513	78.877	61.140	90.586	87.270
LLT/NPM, FCFS	95.606	78.749	61.066	90.411	86.802
LLT/NPM, FISFS	95.900	78.981	61.419	91.515	87.813
LLT/NPM, SPT	96.111	78.945	61.640	91.308	88.036
FISFS, FCFS	93.216	77.213	60.366	90.342	86.645
FISFS, FISFS	92.985	77.393	60.362	90.055	86.280
FISFS, SPT	93.572	77.743	60.788	90.946	87.365
SPT, FCFS	95.450	79.653	59.463	86.746	83.538
SPT, FISFS	95.016	79.997	59.232	87.838	84.412
SPT, SPT	95.415	80.088	59.993	88.807	85.787
SLT, FCFS	91.021	76.797	55.801	82.366	79.143
SLT, FISFS	91.671	76.142	59.111	87.657	84.379
SLT, SPT	90.642	76.592	56.861	83.346	80.928
Mixed 1	96.256	79.492	61.871	91.411	87.738
Mixed 2	96.236	79.538	61.777	90.721	87.693
Mixed 3	95.818	79.148	61.365	91.112	87.349
Mixed 4	95.689	78.998	61.288	90.414	87.009
Mixed 5	96.311	78.978	61.764	91.857	88.119
Mixed 6	95.614	78.539	61.194	90.914	87.283
Mixed 7	95.822	78.483	61.439	91.334	87.589

APPENDIX C

MACHINE UTILIZATIONS (%)

	Shop Section				
Alternative	1	2	3	4	5
LQ, FCFS	34.274	32.558	43.092	40.733	28.469
LQ, FISFS	34.164	32.352	42.711	40.400	28.204
LQ, SPT	34.283	32.542	42.924	40.570	28.246
LLT, FCFS	34.555	32.438	42.770	40.230	28.115
LLT, FISFS	34.038	32.202	42.373	40.381	28.158
LLT, SPT	34.121	32.294	42.695	40.422	28.258
LLT/NPM, FCFS	34.091	32.236	42.565	40.333	28.112
LLT/NPM, FISFS	34.230	32.394	42.735	40.833	28.442
LLT/NPM, SPT	34.275	32.430	43.003	40.815	28.523
FISFS, FCFS	32.928	31.388	42.070	40.278	28.065
FISFS, FISFS	32.870	31.434	41.997	40.167	27.946
FISFS, SPT	30.025	31.534	42.203	40.559	28.288
SPT, FCFS	33.942	32.262	40.681	38.696	27.062
SPT, FISFS	34.072	32.446	41.265	39.200	27.350
SPT, SPT	34.038	32.566	42.003	39.626	27.796
SLT, FCFS	32.653	30.923	38.868	36.690	25.596
SLT, FISFS	32.364	30.928	41.157	39.111	27.338
SLT, SPT	32.626	31.062	39.803	37.189	26.215
Mixed 1	34.368	32.524	42.997	40.781	28.419
Mixed 2	34.357	32.692	43.168	40.467	28.408
Mixed 3	34.225	32.408	42.700	40.630	28.288
Mixed 4	34.153	32.344	42.686	40.333	28.185
Mixed 5	34.421	32.458	43.030	40.967	28.546
Mixed 6	34.109	32.216	42.589	40.519	28.273
Mixed 7	34.204	32.226	42.770	40.737	28.369

APPENDIX D

SETUPS PER HOUR

	Shop Section				
Alternative	1	2	3	4	5
LQ, FCFS	9.61	19.03	6.33	.90	.13
LQ, FISFS	9.58	17.96	6.17	.89	.12
LQ, SPT	9.48	18.74	6.59	1.01	.16
LLT, FCFS	9.81	19.35	6.45	1.03	.13
LLT, FISFS	10.04	18.36	6.50	1.03	.16
LLT, SPT	9.88	18.48	6.71	1.11	.17
LLT/NPM, FCFS	9.59	17.83	6.27	.95	.15
LLT/NPM, FISFS	9.90	16.63	6.48	.94	.16
LLT/NPM, SPT	9.77	16.97	6.71	1.02	.17
FISFS, FCFS	14.19	25.55	6.82	.98	.18
FISFS, FISFS	14.05	26.67	6.89	1.05	.18
FISFS, SPT	14.21	24.49	6.99	1.02	.18
SPT, FCFS	15.35	27.74	6.23	.90	.12
SPT, FISFS	15.22	26.15	6.30	.94	.13
SPT, SPT	15.25	27.41	6.72	.96	.15
SLT, FCFS	14.42	27.73	6.65	1.18	.23
SLT, FISFS	13.50	26.90	6.85	1.09	.20
SLT, SPT	13.96	27.29	6.81	1.19	.23
Mixed 1	9.64	17.98	6.56	.92	.15
Mixed 2	9.54	18.82	6.64	1.01	.15
Mixed 3	9.66	17.90	6.49	.95	.16
Mixed 4	9.60	17.69	6.37	.95	.15
Mixed 5	10.13	15.54	6.78	.95	.16
Mixed 6	9.82	16.52	6.69	.98	.16
Mixed 7	10.02	15.26	6.72	.93	.15

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